Computer Networks 112 (2017) 223–236

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Energy-efficient virtual topology design in IP over WDM mesh networks☆

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ARTICLE INFO

Article history:
Received 13 June 2016
Revised 19 October 2016
Accepted 22 November 2016
Available online 23 November 2016

Keywords:
IP over WDM
Energy efficiency
Virtual topology
Survivability

ABSTRACT

Energy efficiency has been well recognized as an important objective in design of IP over WDM mesh networks. While previous works always focus on energy minimization through green routing and resource provisioning, the comprehensive performances of the two-layer network cannot be guaranteed. This would be not good for realization of energy-efficient networking methods.

In this paper, we first study the problem of getting a good tradeoff between the three-part network comprehensive performances: energy efficiency, resource efficiency and cross-layer survivability efficiency for IP over WDM mesh networks under the static traffic demand. We present the virtual-link energy model for two-layer networks. The energy model is computed from the power consumption value of commercial network devices. Based on the energy-aware two-layer auxiliary graph, we propose a new Energy-Efficient Virtual Topology Design (E^2VTD) scheme. The novelty of our proposed E^2VTD scheme is mainly twofold as following: the first is the energy-efficient virtual link direct mapping and rerouting and the second is the cross-layer survivability improvement for energy-efficient virtual topology. We use extensive simulations to demonstrate the efficiency of our proposed E^2VTD scheme. It is shown that the network comprehensive performances are significantly improved for two-layer networks. Compared with the previous algorithms, network energy consumption is reduced by about 39.8%, network resource is reduced by about 28.2%, and cross-layer topology survivability can be enhanced by about 35.7% in average.

1. Introduction

The traffic volume that needs to be transported by communication networks is growing very fast due to the continuously increasing number of end-users and to the new emerging application services that can be accessed to the network. This reflects into a need for increased network capacity, which in turn results in higher energy consumption [1]. This contributes to the increasing energy consumption of the ICT (Information and Communication Technology) field which currently represents about 8% [2] of the total electricity consumption all over the world. It becomes evident that research on technologies, methodologies and approaches that can offer energy efficiency are of the utmost importance. In this paper, we concentrate on problem of energy-efficient core networks. It is widely accepted that optical transmission technologies [3–5] will have a central role in the formation and the support of the core network of the future. Thus it is necessary to explore new solutions with respect to optical network's energy efficiency.

Compared with the research of one-layer green optical networks, the energy minimization of two-layer IP over WDM mesh networks is more important because the energy of IP/MPLS router port is far greater than that of optical transmission equipments [6–8]. In our opinion, it should not only emphasize energy efficiency for IP over WDM mesh networks. In networks some links are turned into sleep status during non-peak time for energy-saving purpose, which inevitably decreases the survivability of topology.

☆ This work is partially supported by China's 973 Program (2013CB329103), NSFC Fund (61271165, 61301153), Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT), the 111 Project (B14039), Shanghai Oriental Scholar Program, Science and Technology Program of Sichuan Province (2016GZ0138, 2016GZ0107) and The National Natural Science Foundation of China (NSFC) under Grant 61671124.

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http://dx.doi.org/10.1016/j.comnet.2016.11.016
1389-1286/

Moreover, traditional research works on IP over WDM mesh networks is always to minimizing network resource (i.e., improving resource efficiency). This objective seems to be similar with energy efficiency from some aspect, but not completely identical. The relationship between energy efficiency and resource efficiency needs to be analyzed in detail. In this paper we first research the problem of how to balance the three-part network comprehensive performances: energy efficiency, resource efficiency and cross-layer survivability efficiency in two-layer networks. In what follows, we will outline previous work and motivate our study.

1.1. Previous work

The problem of energy-efficient IP over WDM mesh networks under the static traffic demand has been studied by several researches in the literature. In [8], the concept of energy-efficient IP over WDM mesh networks is first introduced. The authors of [8] presented the energy consumption minimization mathematic model, and propose two heuristics based on lightpath strategy: Direct Bypass and Multi-hop Bypass. While the heuristics of [8] select the shortest path on the virtual topology to improve capacity utilization, the authors of [9] analyze the layered architecture of IP over WDM mesh networks and present Auxiliary Graph (AG) model. Two energy-aware heuristics are proposed: Request Size Based (RSB) and Link Utilized Based (LUB) which find the shortest path from (s, d) node pair on AG model. Similar with [9], the authors of [10] propose three categories of heuristics: path based, link based and flow deviation which are all based on *Dijkstra*'s shortest path algorithm. The authors of [11] analyze transport architectures of IP over WDM mesh networks, and find that IP with Bypass and Grooming (IP-BG) performs best in energy efficiency and network cost. The works of [8–11] perform energy minimization in IP over WDM mesh networks from the respect of resource optimization. When routing connections and resource allocation in two-layer networks, these works do not consider energy consuming factor, but resource factors (e.g., hop minimization or distance minimization). The authors of [12] present operational energy model of IP over WDM mesh networks, and propose power-aware provisioning algorithm based on the energy-aware link weights. In [12], when deploying connection request into the network, the newly increased of energy consumption is minimized. But the whole network energy consumption cannot guarantee the global optimum. Ricciardi et al. [13,14] try to reduce both the energy cost and Green House Gases (GHG) emission by leveraging renewable energy sources. However, they consider these two objectives separately, rather than pursue them as an joint optimization. Mandal et al. [15] presents another algorithm to reduce both the energy consumption and the workload on the CDN based on a hybrid CDN-P2P system in an IP-over-WDM network. In fact, it exploits P2P system to reduce workload on the CDN, but not dealing with the energy consumption directly. In [16], an energy model is proposed with the concept that the consumption will scale with the traffic speeds and volumes processed and also depend on the type of processing required. Similarly, Ricciardi et al. [17] presents a hybrid routing and wavelength assignment algorithm to make the switching decision among load-balancing and energy-awareness. Ricciardi et al. [16,17] focus on single network performance, rather than multiple objectives as in our work.

While the above studies always focus on energy minimization of two-layer networks, but how to guarantee comprehensive performances of energy-efficient IP over WDM mesh networks is an open issue for future investigation. Sleeping low loaded network equipment and reroutes the traversing traffic to other areas is a fundamental method for reducing energy consumption of networks. Since traffic demands always change in different time periods, the energy-efficient network design is to determine the effective routing and optimal topology in order to minimize the non-necessary links or nodes, which means the traffic is aggregated in residual links. This would decrease the topology connectivity. Careful attention should be paid onto the tradeoff between energy consumption and network survivability performance. On the other hand, in general decreasing the network resource in IP over WDM mesh networks may also reduce the network energy consumption. This indicates that power efficiency can be improved by smart virtual topology design and traffic grooming method. But the grooming policy in previous works focuses on two-layer network resource utilization improvement, not directly considers energy consumption factor. The two objectives do not completely coincide.

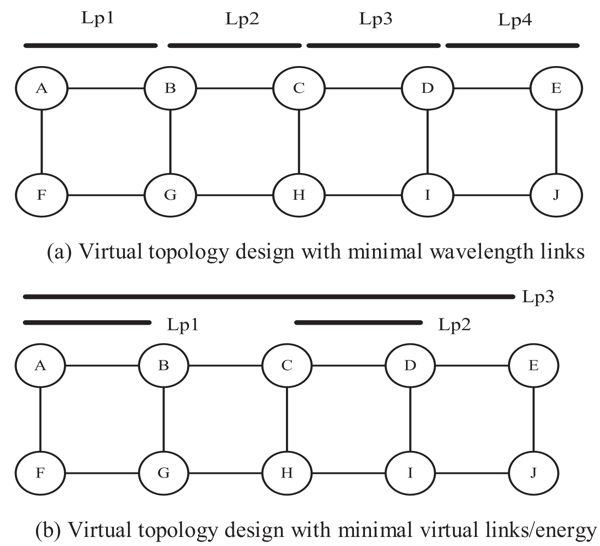


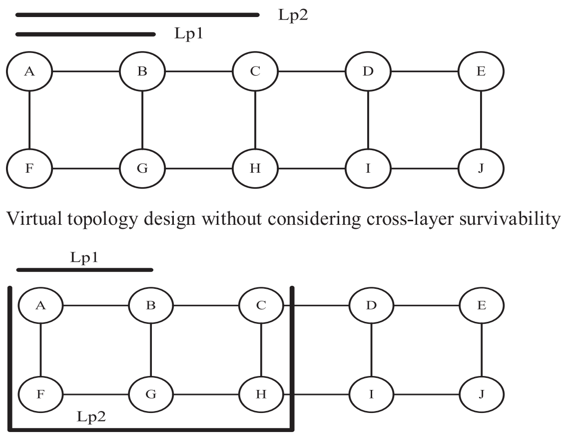
Fig. 1. Virtual topology design example 1.

1.2. Motivation

In this paper, we study the problem of getting a good tradeoff between three main comprehensive performances in IP over WDM mesh networks: energy efficiency, resource efficiency and cross-layer survivability efficiency. The definition of energy efficiency is the minimization of network energy consumption; the definition of resource efficiency is the minimization of network resource, which means that the number of virtual links (i.e., lightpaths) or wavelength links in the network is minimized; the definition of cross-layer survivability efficiency is to maximize virtual topology survivability, which means the single physical link failure on bottom layer induces the minimum number of connection requests' disruption on top layer. To illustrate the importance of virtual topology design in energy-efficient IP over WDM mesh networks, we give two examples in Figs. 1 and 2.

In Fig. 1, we assume there are three connection requests to be deployed in the network: C_1 (A-B), C_2 (C-D), and C_3 (A-E). Fig. 1(a) illustrates virtual topology design results with minimal wavelength links: Lighpath 1 (in the following part of the paper, we abbreviate Lightpath as Lp) carries connection C_1. Lp3 carries connection C_2, and C_3 is groomed into Lp1-4.

The virtual topology of Fig. 1(a) occupies four wavelength links and four Lps. Fig. 1(b) illustrates virtual topology design results with minimal virtual links: Lp1 carries connection C_1, Lp2 carries connection C_2, and Lp3 carries connection C_3. The virtual topology of Fig. 1(b) occupies 6 wavelength links and three Lps, and the virtual links is minimized. As the energy consumption of electronic port (i.e., the transceiver port of virtual link) is much higher than



(a) Virtual topology design without considering cross-layer survivability

(b) Virtual topology design considering cross-layer survivability

Fig. 2. Virtual topology design example 2.

that of other components of IP over WDM networks [18], the network energy of Fig. 1(b) is obviously less than that of Fig. 1(a).

In Fig. 2, we assume there are two connection requests to be deployed in the network: C_1 (A-B) and C_2 (A-C). Fig. 2(a) illustrates virtual topology design results without considering cross-layer survivability: Lp1 carries connection C_1 and Lp2 carries connection C_2. The virtual topology of Fig. 2(a) occupies three wavelength links and two Lps. From the perspective of resource and energy efficiency, the virtual topology of Fig. 2(a) is optimal. But when fiber link A-B fails, Lp1 and Lp2 both disrupt. Fig. 2(b) illustrates the virtual topology considering cross-layer survivability. In Fig. 2(b), the physical path of Lp2 is changed to A-F-G-H-C. Thus the failure of fiber link A-B disrupts only Lp1. It is noticeable that the cross-layer survivability of Fig. 2(b) is enhanced 100% than that of Fig. 2(a). But the whole network energy slightly increases. The reason is that the energy consumption value of wavelength links is minor in IP over WDM mesh networks (See in Sec. III). We note that for energy-efficient two-layer networks, cross-layer survivability is an important issue under careful investigation especially in the scenario of low traffic demands, where many links in the network are turned into sleep status.

1.3. Contribution

As far as we know, in this paper we first study the problem of guaranteeing comprehensive performances of energy-efficient IP over WDM mesh networks. Our objective is to get a good tradeoff between energy efficiency, resource efficiency and cross-layer survivability efficiency. We first carry out a power consumption analysis for each device in IP over WDM mesh networks, and present the lightpath-based energy model to facilitate top-layer connections green deployment. We call it “virtual link” energy model. From the energy model, we propose the Energy-Efficient Virtual Topology Design (E^2VTD) scheme. The novelty of the E^2VTD is mainly twofold: the first is the energy-efficient virtual link direct mapping and rerouting; the second is the cross-layer survivability improvement for energy-efficient virtual topology. Results from extensive simulation results conducted on three typical carrier mesh networks testify the efficiency of our proposed E^2VTD scheme.

The rest of this paper is organized as follows. Section II formally presents the network model under consideration. Section III presents the virtual link energy model for IP over WDM mesh networks. Section IV describes in detail the proposed novel scheme. Section V presents numerical results and Section VI concludes this paper

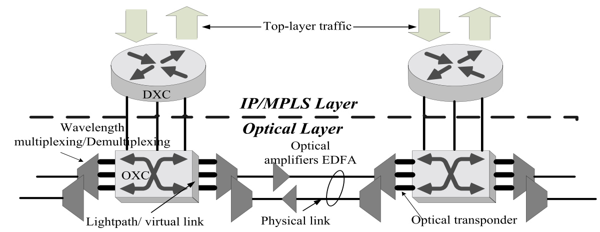


Fig. 3. Architecture of IP over WDM mesh networks.

2. Network model and problem statement

The general problem of energy-efficient IP over WDM mesh networks is formally stated below. Here we give the following inputs to the problem:

- A physical IP over WDM mesh network topology $\boldsymbol{G}(\boldsymbol{V}, \boldsymbol{E})$ consists of a weighted unidirectional graph, where $\boldsymbol{V}$ is the set of network nodes and $\boldsymbol{E}$ is the set of physical links connecting the network nodes. Nodes correspond to network nodes and links that is unidirectional correspond to the fibers between nodes. V and E denote the node number and the unidirectional link number in the physical network, respectively. We assume that there is one single fiber joining two nodes in different directions. Links are assigned weights, which may correspond to the physical distance between nodes.
- A network node has wavelength conversion capability. The transceivers in a network node are tunable to any wavelength on the fiber, and a network node has enough transceivers.
- A connection can traverse multiple lightpaths before it reaches the destination. So a connection may be groomed with different connections on different lightpaths.
- There exist four types of low-speed connections in the two-layer mesh network: OC-1, OC-3, OC-12, and OC-48; the corresponding granularity is 1, 3, 12, and 48 respectively. Every connection has to be routed on a single path in the virtual topology, which means single connection cannot be divided again.
- Capacity of one wavelength is OC-192 (10 Gbps), and the granularity is 192.

Our goal is to determine the following. Given a physical network topology and a set of multi-granularity connection requests, we study on getting a good tradeoff between the three-part comprehensive performances: energy efficiency, resource efficiency and cross-layer survivability efficiency.

3. The virtual link energy model

3.1. Architecture of IP over WDM mesh networks

The architecture of IP over WDM mesh networks is illustrated in Fig. 3. In such an architecture, IP/MPLS router (or DXC) ports are connected to the ports of WDM optical crossconnects (OXCs), and OXCs are interconnected in a mesh configuration with fiber links. The packets traffic from access networks in the electronic domain are accumulated into an IP router attached to an OXC. The electronic packets are converted to an optical signal, and then are transmitted via fiber links. On optical layer for a single fiber, a pair of wavelength multiplexers/demultiplexers on optical switching node is employed to multiplex/demultiplex wavelengths. Associated with each wavelength, a pair of transponders is connected for data transmission. Besides, to assure optical signals to travel a long distance, optical amplifiers such as EDFA are deployed on fiber links.

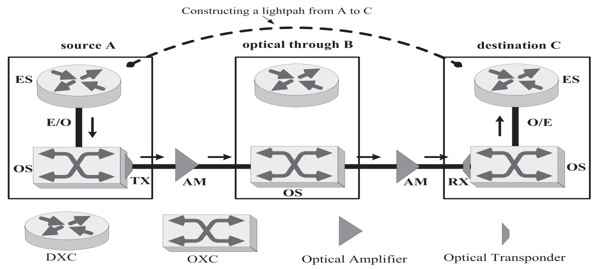


Fig. 4. Process of lightpath establishment in IP over WDM mesh networks.

3.2. The virtual link energy model design

The nomenclatures in the virtual link energy model are shown as following. *number_AM*: the number of amplifier of the link. *link*(*m, n*): the link from node *m* to node *n*. *number_internode*: the number of intermediate nodes for the lightpath. $dist_{mn}$: the distance of link(*m, n*). *Traffic_volume*: the traffic capacity of electronic switching. d_0: the interval distance for amplifier deployment.

We design the energy model of IP over WDM mesh networks based on the granularity of lightpath (i.e., virtual link). We call it "virtual link" energy model. The reason is that in such a two-layer network, the virtual link is the electron/optics hybrid channel transmitting connections. The energy-efficient configuration of IP over WDM is a set of routing-fixed lightpaths on which the working/backup path of connection is routed. Note that we are not claiming any novelty in the energy model of two-layer networks, but discuss here to make the paper more complete. We will use the virtual link energy model to guide the design and evaluate the effectiveness of our proposed E^2VTD scheme.

(*1*) *Process of lightpath establishment*

We first illustrate the lightpath establishment process in Fig. 4. We observe that the process can be divided into four parts as follows. Source node A: a) traffic arrives on electronic router of source node A; b) traffic completes Electronic Switching (i.e., ES) in router; c) the electronic signal on the linecard of IP/MPLS router is transformed to optical signal (i.e., E/O); d) the signal is Optically Switched (i.e., OS) in OXC; e) the optical signal is transmitted (i.e., TX) by transponder. Fiber links: the optical signal is amplified (i.e., AM) by EDFAs, and the number of EDFAs is determined by the distance of the span. Intermediate node B (optically passing through): the signal is OS in OXC of traversing intermediate nodes. Destination node C: a) the optical signal is received (i.e., RX) by transponder; b) the signal is OS in OXC; c) the optical signal is transformed to electronic signal (i.e., O/E) on the linecard of IP/MPLS router; d) traffic complete ES in router; e) traffic is exported to the access routers.

(2) *Virtual link energy model design from equipment port*

From the illustrated lightpath establishment, we conclude that the virtual link energy model is shown in Eq. (1):

$$P_{lightpath} = P_{source\_node} + P_{fiber\_links} + P_{intermediate\_node} + P_{destination\_node} \tag{1}$$

In Eq. (1),

$$P_{source\_node} = P_{ES} + P_{E/O} + P_{OS} + P_{TX} \tag{2}$$

$$\begin{aligned} P_{fiber\_links} &= (number\_AM)^{*} P_{AM} \\ &= \sum_{link(m,n)\in LP} P_{mn} = \sum_{link(m,n)\in LP} P_{AM}\left(\left\lceil \frac{dist_{mn}}{d_0} - 1 \right\rceil + 2\right) \end{aligned} \tag{3}$$

$$P_{intermediate\_node} = (number\_internode)^{*} P_{OS} \tag{4}$$

Table 1
Energy consuming parameter value.

Parameter	Explanation	Referring value
p_{ES}	Consuming power of unit traffic volume for Electronic Switching	6.75 W/Gbps
$P_{transponder}$	Consuming power of transponder	38.75 W/wavelength
$P_{linecard\_port}$	Consuming power of linecard port for OC-192	588 W (The linecard undertake an OC−192 signal, 10 Gbps)
P_{OSP}	Consuming power of Optical Switching Port per wavelength	2 W/wavelength
P_{AM}	Consuming power of EDFA amplifier	0.91 W/wavelength
d_0	Distance interval for amplifier placement	80 km
$P_{A/D}$	Consuming power of Add/Drop	1 W/wavelength

$$P_{des\_node} = P_{RX} + P_{OS} + P_{O/E} + P_{ES} \tag{5}$$

We get:

$$\begin{aligned} P_{lightpath} = &\ 2^{*} P_{ES} + P_{TX} + P_{RX} + P_{O/E} + P_{E/O} \\ &(number\_internode + 2)^{*} P_{OS} \\ &+ \sum_{link(m,n)\in LP} P_{AM}\left(\left\lceil \frac{dist_{mn}}{d_0} - 1 \right\rceil + 2\right) \end{aligned} \tag{6}$$

In our study, we assume the IP/MPLS router is Cisco CRS-1 with linecard port OC−192 (approximately 10 Gbps), and WDM layer node is Cisco ONS15454 with 40-wavelength system of OXC [19,20]. For network devices of IP over WDM networks, SC (Switching Card) completes ES, LC (LineCard) of IP/MPLS router completes E/O and O/E process; transponders complete lightpath receiving and transmitting (i.e., TX and RX); for the lightpath passing through inter-node two Optical Switching Ports (OSP) jointly complete OS, for lightpath terminating node (i.e., source and destination), one Optical Switching Port and one Add/Drop Port jointly complete OS. Then Eq. (6) can be turned into:

$$\begin{aligned} P_{lightpath} = &\ 2^{*}(P_{SC} + P_{transponder} + P_{linecard\_port} + P_{A/D}) \\ &+ 2^{*}(number\_internode + 1)^{*} P_{OSP} \\ &+ \sum_{link(m,n)\in LP} P_{AM}\left(\left\lceil \frac{dist_{mn}}{d_0} - 1 \right\rceil + 2\right) \end{aligned} \tag{7}$$

$$P_{sc} = p_{ES}{}^{*} Traffic\_volume \tag{8}$$

Table 1 gives the referring value of parameters in Eqs. (7) and (8). The parameters used in equations are calculated from the commercial devices' power values in [21,22]. For example, the authors of [21] illustrate that the linecard port of Cisco CRS-1 with 10 Gbps consumes 588 W. On the optical layer, Cisco ONS15454 with 40 wavelengths consumes 80 W, that is, 2 W per port for optical switching. The power of EDFA amplifier is 36.25 W [22], for a fiber with 40 wavelengths meaning 0.91 W per wavelength. With the above parameter values, combining with our proposed virtual link energy model, we can calculate the energy consumption of whole network as Eq. (9).

$$P_{network} = \sum_{num\_lightpath} P_{lightpath} \tag{9}$$

3.3. IP over WDM network energy analysis

In general, decreasing the number of lightpaths in IP over WDM networks may reduce the network energy because the consuming power of linecard port (i.e., 588 W) in Table 1 is much higher than

Table 2
Notations used in this paper.

Symbol	Means
G(V,E)	A graph that represents the physical network
V	The set of nodes of ***G***
E	The set of edges of ***G***
c	The connection request on IP/MPLS layer
s_c	Source node of *c*
d_c	Destination node of *c*
Bd_c	The bandwidth requirement of *c*
h_c	The minimum hop between s_c and d_c
wp_c	The working path of *c*
bp_c	The backup path of *c*
LP	Lightpath of the network
Cap	The available capacity of *LP*
S	The original set of connection requests
S'	The sorted set of connection requests
VT	The virtual topology in the network for the connection requests, i.e., ***VT*** = {*LP*}
NetP	Network power consumption of the network
s_{LPE}	Source node of LP
d_{LPE}	Destination node of LP

other values. This indicates power efficiency can be improved by smart traffic grooming method. Though less number of lightpahs in network means smaller energy consumption for network, energy consumption of process for lightpath establishment needs to be carefully differentiated. The previous studies have shown typical energy values for the above processes, and conclude that electron-related process consumes significantly more power than optic-related process. From this point, traffic using end-to-end grooming (i.e., single lightpath) reduces energy than hop-by-hop grooming (i.e., multiple lightpaths) method which means more O-E-O procession and electronic switch. However, end-to-end grooming also increase the number of lightpaths which instead increase the energy of the network.

4. The proposed E^{2}VTD scheme

In this section, we first present an auxiliary graph model for energy-efficient routing, and propose a novel E^{2}VTD scheme which provides a good tradeoff between energy efficiency, resource efficiency and cross-layer survivability efficiency. The E^{2}VTD scheme includes two parts as following. The first part is the Virtual Link Direct Mapping and Rerouting (VLDMR) algorithm. The second one is the Energy-efficient Cross-layer Survivability Improvement (ECSI) algorithm. The symbols we used in this section and their means are shown in Table 2.

4.1. Two-layer energy-aware auxiliary graph model

The Auxiliary Graph (AG) method for IP over WDM mesh networks has been presented extensively in the previous works [23–25]. In our proposed E^{2}VTD, to facilitate the route computing and resource deployment, a two-layer Energy-Aware Auxiliary Graph (EAAG) Model is generated. In EAAG, layer 1 denotes the optical layer and layer 2 denotes the electronic layer. There are all three kinds of edges: Physical Link Edge (PLE), Optic/Electron Hybrid Edge (OEHE) and LightPath Edge (LPE). The PLE connects the optical layer of one node to the optical layer of other node and denotes the physical fiber link on the bottom layer. The OEHE connects the optical layer and the electronic layer within a node and denotes the O/E and E/O conversion. The LPE connects the electronic layer of one node and the electronic layer of other node and denotes the virtual link of the two-layer network. Two segments of OEHE and a few segments of PLE can construct one LPE on the top layer. According to the virtual link energy model, when constructing a new LPE in EAAG, the power consumption of a PLE mainly consists of the power of optical switching port and the power of EDFAs on the fiber link; the power consumption of a OEHE mainly consists of the power of linecard port, the power of transponder and the power of Add/Drop, etc. When utilizing EAAG to calculate energy-efficient routing for connection requests, we set the weight of the three kinds of edges as the power consumption numerical values. This means would guarantee the power consumption minimization of the whole network when provisioning network resource to connection requests. The detail of edge weight setting in EAAG is given in the E^{2}VTD scheme.

In the following, we use a six-node topology to illustrate the EAAG (shown in Fig. 5(a)). Nodes labeled from A to F indicate two-layer nodes in the network. Fig. 5(b) shows four connection requests: A->B, B->D, D->C, and A->D. Fig. 5(c) shows the corresponding EAAG, where each node is separated into electronic node and optical node. In Fig. 5(c), lightpath A->B is built for connection A->B and it is mapped as Ae-Ao-Bo-Be on the bottom layer; lightpath B->D is built for connection B->D and it is mapped as Be-Bo-Do-De on the bottom layer; lightpath D-C is built for connection D->C and it is mapped as De-Do-Eo-Co-Ce on the bottom layer. Connection A->D is multi-hop groomed into the existing lightpath A->B and lightpath B->D. From the example of Fig. 5, by EEAG we can easily calculate the energy-efficient routing path for low-speed connections through intelligently selecting "hop-by-hop grooming" or "end-to-end grooming" strategy on the virtual topology.

4.2. VLDMR algorithm

The objective of the VLDMR algorithm is to achieve the energy-efficient virtual topology in IP over WDM mesh network. The algorithm first tries to carry the working path of all connection requests by direct virtual link, and then tears down low-utilization lightpaths with rerouting method to further reduce power consumption of the network. A more detailed version (pseudocode) of the algorithm can be found in Fig. 6. An explanation of the pseudocode is given below.

- ***Line 1***: Compute the minimal hop/distance path h_c for node pair of each connection request in ***S***.
- ***Line 2***: Sort connection requests by hop ascending order. If some connection requests have the same hop value, sort them again by bandwidth descending order. When sorting completed, save the newly ordered requests in ***S***′.
- ***Line 3***: Initialize the virtual topology. As the problem studied in this paper is a network provisioning problem, the initial virtual topology is empty.
- ***Line 4–7***: Route all connection requests of ***S'*** into the two-layer network. For each connection, the *direct_mapping_method()* function calculates the energy-efficient routing in EAAG with the virtual link direct mapping method, which means the connection request must be traversed by the direct lightpath of the (s_c, d_c) node pair, cannot use multi-hop lightpaths. There are two situations for the virtual link direct mapping method. In *situation 1*, the current ***VT*** may not have the direct virtual link, and then a new direct LP needs to be constructed. In *situation 2*, the current ***VT*** may have the direct virtual link *LP* with enough spare capacity, the connection request is groomed into the *LP*. The power weight of edges in *direct_mapping_method()* function is shown in Eq. (10), where the first line illustrates the power weight of PLE; the second line illustrates that of OEHE, and the last line illustrates that of LPE when spare capacity of *LP* can afford the connection. The power weights of PLE and OEHE are used for routing in *Situation 1*, and the power weight of LPE is used for routing in *Situation 2*. We perform the edge weight's assignment and run *Dijkstra*'s shortest path algorithm to get the

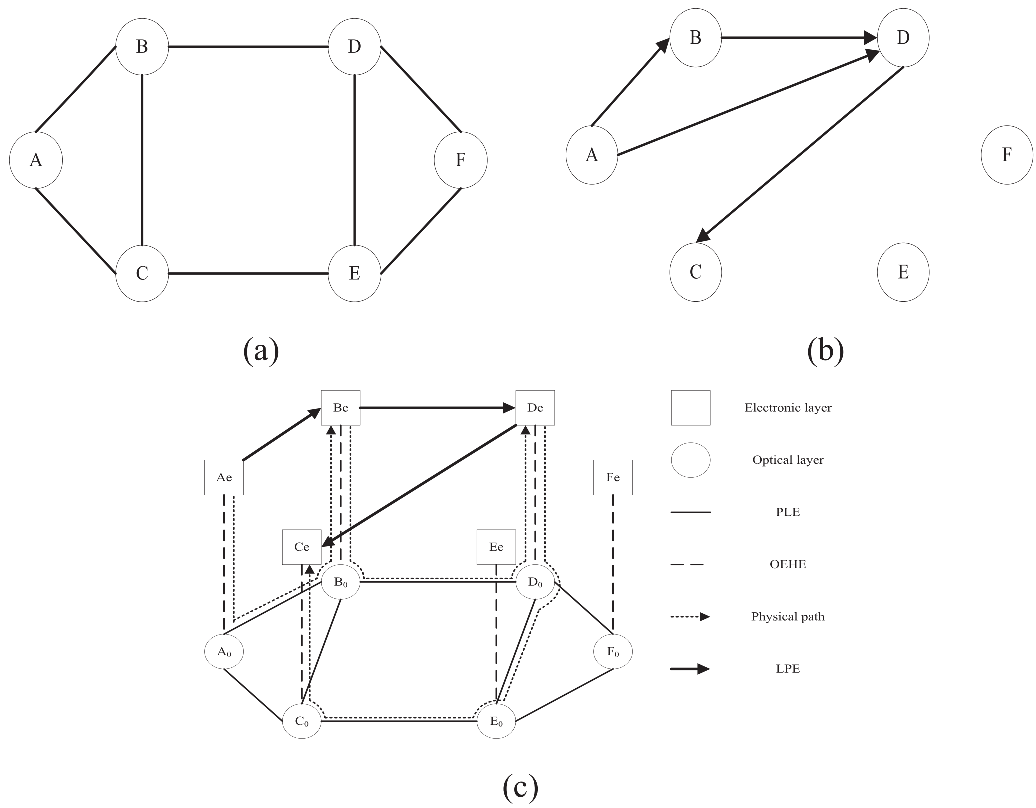


Fig. 5. Two-layer EEAG example (a) physical topology (b) four connection requests (c) auxiliary graph.

Virtual Link Direct Mapping and Rerouting

Input:
(a) A physical network ***G*** (***V***, ***E***);
(b) The virtual link energy model;
(c) A set of connection requests ***S***.
Output:
An energy-efficient virtual topology with minimize energy consumption for IP over WDM mesh network.
Algorithm:

```
1   Compute the minimal hop/distance path h_c for node pair
    of each connection request c in the network.
2   Sort requests in S and save the ordered requests in S'
3   Initialize VT= Φ.
4   for (each connection c in S')
5       wp_c= direct_mapping_method(c, VT)
6       update (VT)
7   end for
8   Sort lightpaths in VT
9   for (each LP in VT)
10      delete LP from VT
11      if (reroute(c, VT)==false)
12      resume LP to VT
13      else
14      update (VT)
15  end for
16  NetP=Power(VT)
17  Return(NetP)
```

Fig. 6. The pseudocode of VLDMR algorithm.

minimal power weight path for the connection request. When deploying each connection request into the network, the virtual topology ***VT*** continues to increase. And the available capacity of each LPE in ***VT*** needs to be updated.

- ***Line 8***: Sort lightpaths in current ***VT*** by the utilization ascending order. The definition of utilization is the ratio of working capacity to total capacity of lightpath.
- ***Line 9–15***: To further reduce power consumption of network, we hope to minimize the number of lightpaths of ***VT***. We in turn delete the lowest utilization lightpath, and reroute the connection requests deployed on this lightpath on residual ***VT***. The routing and resource allocation function *reroute()* is mainly similar with the aforementioned direct mapping algorithm, the weight of LPE will be set to 1 while the weight of PLE and OEHE will be set to infinite so that no new lightpath would be built. If the routing is not successful, resume the deleted *LP* to ***VT*** and go to the next *LP* until all *LP*s of ***VT*** are traversed.
- ***Line 16–17***: Based on the energy model summarized before, we get the power consumption of the network.

$$W_d = \begin{cases} P_{OSP} \times 2 + P_{AM} \times ([dist/d_0 - 1] + 2) \quad if \quad e \in PLE \\ P_{linecard\_port} + P_{transponder} + Bd_c \times P_{ES} + P_{A/D}\, if\; e \in OEHE \\ Bd_c \times P_{ES} \times 2\, if\; (e \in LPE) \cap (Bd_c < Cap) \\ \quad \cap (s_c = s_{LPE}) \cap (d_c = d_{LPE}) \end{cases} \tag{10}$$

The VLDMR algorithm consists of two phases. The first phase consists of ***Line1*** to ***Line 7*** and the second phase consists of ***Line 8*** to ***Line 17*** in Fig. 9. In the first phase, the algorithm attempts to carry the working path of all connection requests by the direct mapping method. The method first attempts to route the path in the direct *LP* of the current ***VT***, update the spare capacity of ***VT***; if not successful a new direct *LP* between the (s_c, d_c) node pair would be established, then add the new *LP* to the ***VT***.

For further explanation, we compare our proposed direct mapping method with the previous energy-efficient method such as Multi-hop Bypass [8], and PAR (Power-Aware Provisioning) [12] in

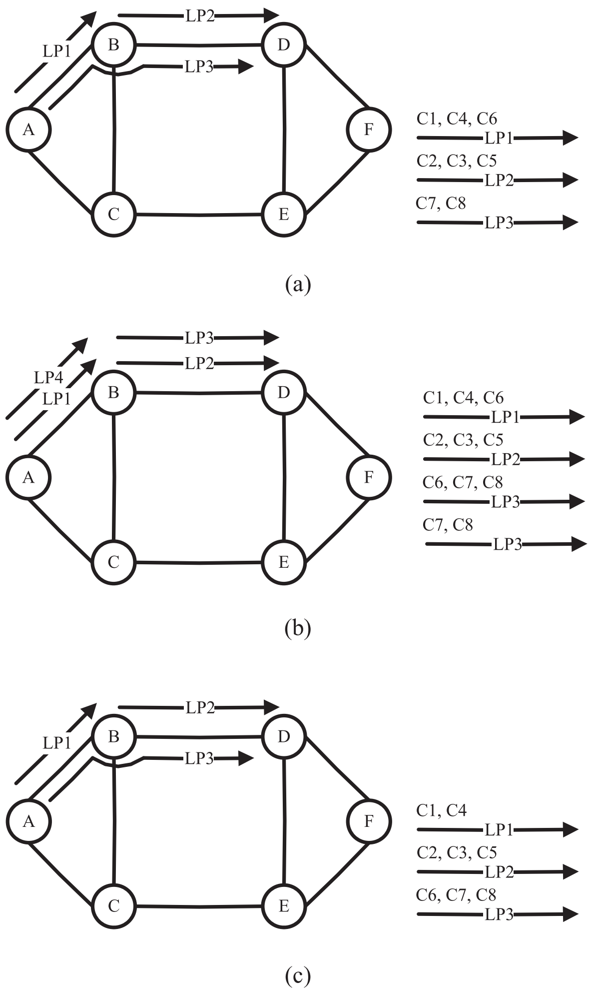


Fig. 7. Illustration for three algorithm of routing path for request (a) Multi-hop bypass (b) PAR (c) direct mapping.

an example shown in Fig. 7. We assume that there are eight connection requests to be deployed into the network. The connection requests are given in the form (s_c, d_c, Bd_c): C1 = (A, B, OC-48), C2 = (B, D, OC-48), C3 = (B, D, OC-48), C4 = (A, B, OC-48), C5 = (B, D, OC-48), C6 = (A, D, OC-48), C7 = (A, D, OC-48), C8 = (A, D, OC-48), and the capacity of each lightpath is OC-192 (10 Gbps).

As shown in Fig. 7(a), we firstly compute the energy-efficient routing for the above eight connection requests by Multi-hop Bypass. The Multi-hop Bypass algorithm first tends to find the appropriate routing in the current ***VT***, if not be successful then constructs the virtual link between the (s_c, d_c) node pair. In Multi-hop Bypass algorithm, when deploying C1, as the initial virtual topology is empty, LP1 from A->B is built to carry C1. Then LP2 from B->D is built to carry C2. The algorithm selects the existed LP2 for C3, LP1 for C4 and LP2 for C5. C6 is multi-hop groomed in LP1 and LP2. Note that now LP2 has no spare capacity, and thus new LP3 from A->D is built to carry C7 and C8. In the example of Multi-hop Bypass, there are three LPs: LP1 carrying three OC-48 connections (C1, C4 and C6), LP2 carrying four OC-48 connections (C2, C3, C5 and C6) and LP3 carrying two OC-48 connections (C7 and C8). From Eq. (7) and the parameters shown in Table 1, the total energy of Multi-hop Bypass of Fig. 7(a) is 4142.5(1360.76 + 1394.5 + 1331) W.

As shown in Fig. 7(b), we secondly compute the energy-efficient routing for the above eight connection requests by PAR. The PAR

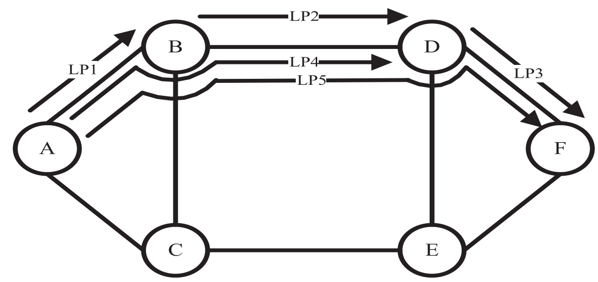


Fig. 8. An example to explain the significance of lightpath deleting.

algorithm finds the appropriate routing in the mixed topology. The mixed topology includes the current virtual topology and physical topology. In PAR algorithm, when deploying C1, as the initial virtual topology is empty, LP1 from A->B is built to carry C1. Then LP2 from B->D is built to carry C2. The algorithm selects the existed LP2 for C3, LP1 for C4, and LP2 for C5. As LP2 now has no free capacity, the algorithm constructs a new LP3 from B->D and C6 is multi-hop groomed into LP1 and LP3. As LP1 now has no free capacity, the algorithm constructs a new LP4 and C7/C8 are both multi-hop groomed into LP4 and LP3. In the example of PAR, there are four LPs built in the network: LP1 carrying three OC-48 connections (C1, C4 and C6), LP2 carrying three OC-48 connections (C2, C3 and C5), LP3 carrying three OC-48 connections (C6, C7 and C8), and LP4 carry two OC-48 connections (C7 and C8). From Eq. (7) and the parameters shown in Table 1, the total energy of Multi-hop Bypass of Fig. 7(b) is 5413.28(1360.76 × 3 + 1331) W.

As shown in Fig. 10(c), we finally compute the energy-efficient routing for the above eight connection requests by our proposed direct mapping method. The method finds the appropriate routing by the direct LP between connection node pairs. Thus in the direct mapping method, LP1 carries C1 and C4; LP2 carries C2, C3 and C5; LP3 carries C6, C7 and C8. From Eq. (7) and the parameters shown in Table 1, the total energy of our proposed direct mapping method of Fig. 7(c) is 4056.48(1331 + 1360.74 + 1364.74) W.

From the example of Fig. 7, we observe that PAR consumes much more power energy than that of other two algorithms, and our proposed direct mapping method performs best in energy efficiency. We analyze the phenomenon in the following. The previous algorithms (e.g., Multi-hop Bypass and PAR) always want to find the optimal energy-efficient routing in the current network status when deploying each connection into the network. But the optimum of one step would not bring out the global optimum of network energy. In the example of Fig. 7, Multi-hop Bypass and PAR try to avoid building a new direct lightpath by deploying the request on existing LPs. Thus connection requests would traverse multiple LPs in the network, which results in network resource/energy inefficiency. Our proposed direct mapping method builds the direct virtual link for connection requests, which can save network power consumption and resource.

However, when there are a little of traffic loads in the network, it is clear that the direct mapping method would construct many low-utilization LPs. This results in resource/energy inefficiency. We give an example in Fig. 8 for illustration. We assume that there are five connection requests to be deployed into the network. The connection requests are given in the form (s_c, d_c, Bd_c): C1 = (A, B, OC-12), C2 = (B, D, OC-3), C3 = (D, F, OC-3), C4 = (A, D, OC-1), C5 = (A, F, OC-1), and the capacity of each lightpath is OC-192 (10 Gbps). By the direct mapping method, we can easily compute the virtual topology result: LP1 for C1, LP2 for C2, LP3 for C3, LP4 for C4 and LP5 for C5. The utilization of the above five LPs is very low, and a large amount of network resource/energy would be wasted.

Therefore, in the second phase of the VLDMR algorithm, the low-utilization LPs are torn down to further reduce power consumption of the network. When the lightpath is deleted, the affected paths of connection requests are routed in the residual virtual topology. For the example of Fig. 8, we first sort lightpaths by utilization ascending order, and the ordered LPs in the network are LP4, LP5, LP2, LP3 and LP1. Then we begin to consider deleting the low-utilization LPs. When deleting LP4 from the virtual topology, C4 should be reroute on the residual virtual topology and the new path for C4 is (LP1 and LP2). Then delete LP5, C5 is rerouted on the new path (LP1, LP2 and LP3). For the residual virtual topology, LP1, LP2 and LP3 would not be deleted, since connections on these LPs cannot reroute. So in the example of Fig. 8, the final energy-efficient virtual topology consists of LP1, LP2, and LP3.

4.3. ECSI algorithm

The objective of the ECSI algorithm is to further enhance cross-layer survivability of the energy-efficient virtual topology constructed by the VLDMR algorithm. There are many parameters can be used to measure the cross-layer survivability, such as the maximum cross-layer min-cut of the network [26] and the maximum number of lightpath that is affected by single-link failure [27]. In this paper, we choose the maximum number of requests that is affected by single-link failure as the cross-layer survivability metric. The ECSI algorithm minimizes this metric with slightly increasing network energy consumption.

There are two methods to improve cross-layer survivability of the virtual topology. The first one is to evenly distribute the requests on lightpaths. The second one is to evenly distribute lightpaths on physical links. If we use the first method to improve cross-layer survivability of the virtual topology, the effort of the VMDLR algorithm will be in vain, because the energy-efficient routing of VLDMR is to aggregate connection requests onto fractional lightpaths to save energy. The second method remaps virtual links onto new physical paths. From the virtual link energy model illustrated in section III, this only increases a small amount of network energy. So we choose the second method for the ECSI algorithm.

From the second method (i.e., virtual link remapping), we formulate an Integer Linear Program (ILP) based on multi-commodity flows, where each lightpath carrying connection requests is considered as a commodity to be route over the physical network. The formulation takes the physical topology and the virtual topology established by the VLDMR as input and uses a general-purpose ILP solver (such as CPLEX) to obtain link-flows in the network.

$$\mathit{Minmize}\, C_W,\ \mathit{subject\ to}:$$
$$C_W \geq \sum_{(s,t)\in E_v} n(s,t) f_{iji}^{st}, \quad \forall(\mathrm{i},\mathrm{j}) \in E_p$$
$$f_{ij}^{st} \in (0, 1)$$
$$\left(f_{ij}^{st} : (i, j) \in E_p\right) \mathit{forms\ an}\ (s, t)\ \mathit{path},\ \forall(s, t) \in E_v$$

In the above ILP formulation, E_P represents the set of links in the physical topology and E_V represents the set of links in the virtual topology. f is the variable set that represents the lightpath routing, so that $f_{ij}{}^{st}=1$ if and only if lightpath (s,t) uses physical link (i,j) in its path. C_w represents the maximum number of requests carried by a physical link in the network. $n(s,t)$ represents the number of requests carried by lightpath (s,t). According to this formulation, the algorithm will try to avoid mapping lightpaths with high $n(s,t)$ on the same physical link. To focus on the survivability aspect of the problem, the wavelength continuity constraint is not considered here.

This multi-commodity flow integer linear program formulation gives a novel way to route lightpaths in a survivable manner, but such approach may not scale to large networks because of the inherent complexity of solving integer programs. We apply randomize rounding technique [28–30] which is able to quickly obtain a near-optimal solution to the ILP to approximate the formulation. Randomize rounding has previously been used to solve multi-commodity flow problems to minimize the load with performance guarantee. The algorithm first tries to calculate an optimal fraction solution by linear relaxation. Then solves the linear relaxation of the ILP and chooses a random physical path between s and t for each lightpath (s,t) with probability based on the fraction solution. With the $RANDOM_k$ method, we can get the final result with the lowest C_w value. A more detailed version (pseudocode) of the algorithm can be found in Fig. 9. An explanation of the pseudocode is given below.

```
Energy-efficient Cross-layer Survivability Improvement
Algorithm
Input:
(a) A physical network G (V, E);
(b) The virtual topology VT created by VLDMR;
(c) Randomize rounding parameter k.
Output:
A virtual topology with higher cross-survivability than before.
Algorithm:
1   calculate an optimal fraction solution by linear relaxation
2   for (each lightpath in VT)
3       choose a random physical path for lightpath
4   end for
5   get a random solution
6   do line 2 – line 5 k times
7   get k random solutions
8   choose the best survivability solution as the final solution
9   return the best solution to VT
```

Fig. 9. The pseudocode of ECSI $RANDOM_k$ algorithm.

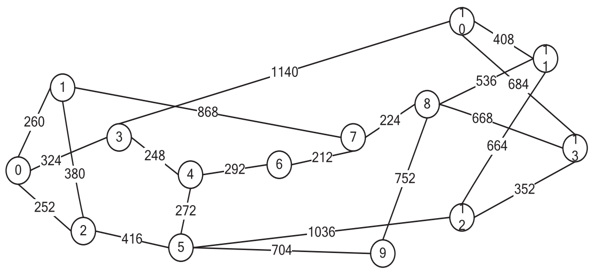
- ***Line 1:*** The algorithm relaxes $f_{ij}{}^{st}$ in ILP to allow it to take on fraction values, which are then used to find the fractional flow through each of a set of alternate paths.
- ***Line 2–4***: For each lightpath in ***VT***, the algorithm chooses a random path between s and t with probability based on the optimal fraction solution obtained from line 1.
- ***Line 5***: After all of lightpaths in ***VT*** routed, there will be a random survivability solution for ***VT***.
- ***Line 6–7***: Do Line 2 to Line 5 k (in our study, $k=100$) times to get k random survivability solutions for ***VT***.
- ***Line 8–9***: From the k solutions, the algorithm chooses the survivability solution with the lowest C_w value as the final survivability solution for ***VT***.

5. Numerical results

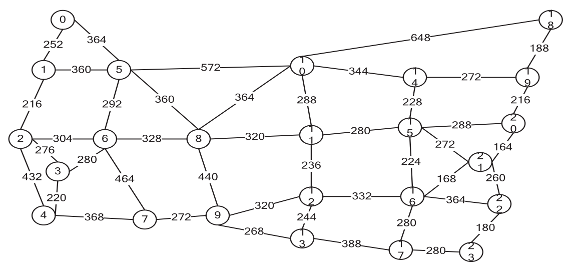
In this section, we present numerical results for our proposed scheme through computer simulations. The algorithms are implemented with C++ and CPLEX 10.0 is the ILP solver. The simulation is carried on a lightly-loaded PC with 2.1 GHz CPU and 2 GB memory. Overall speaking, our algorithms can derive the solution of each point within several seconds, regardless of the demand settings in our simulation.

5.1. Networks and demands

Simulation experiments are performed on the NSFNET that has 14 nodes and 21 bidirectional links (shown in Fig 10(a)) and the USNET that has 24 nodes and 43 bidirectional links (shown in Fig. 10(b)). We simulate the two networks since they represent three



(a) NSFNET Topology



(b) USNET Topology

Fig. 10. Network topologies for simulation.

typical carrier networks and are widely used in the literatures. Each link in these networks represents two bidirectional fiber links in opposite directions. By each link, the physical distance (km) of the link is indicated. In addition, the following inputs were assumed:

(1) Each link has 40 wavelengths. Wavelength capacity is OC-192 (10 Gbps).

(2) The basic bandwidth granularity is OC-1 (51.84 Mbps), and demands are uniformly distributed among OC-1, OC-3, OC-12 and OC-48. We define two types of traffic demands:

- ***Average Demand:*** Traffic Demand of each node pair in the network is a constant.
- ***Random Demand:*** Traffic demand of each node pair in the network is randomly distributed.

5.2. Simulation setup

The simulations are divided into three parts in terms of their compared performances. In the first part, we compare our proposed VLDMR algorithm in the E^2VTD scheme with several green algorithms in network energy performance. In the second part, we use NSFNET as an example to show performance of the ECSI algorithm. This part of simulation is further divided into two subparts. In the first subpart, we compare the virtual topology outputed by the ECSI with the input one (i.e., the energy-efficient virtual topology created by the VLDMR algorithm) in cross-layer survivability and power consumption. In the second part, we compare ECSI with other green algorithms in cross-layer survivability performance. In the third part, we compare the E^2VTD scheme (only including the VLDMR and ECSI algorithm) with other green algorithms in resource performance, including the number of lightpaths, the number of wavelength links and the lightpath utilization.

5.3. Network energy performance

In this part, we investigate the network energy of the five energy-efficient algorithms in IP over WDM mesh networks. The compared algorithms include the Direct Bypass [8], the Multi-hop Bypass [8], the PAR [12], the MTR and our proposed VLDMR. The MTR (Mixed Topology Routing) algorithm is an improved algorithm from the PAR, in which we try to tear down some low-utilization lightpaths in the virtual topology created by the PAR and reroute affected connection requests on the residual virtual topology. This would further reduce network energy of PAR.

Fig. 11(a) and (b) show the power consumption of the five algorithms for NSFNET under Random Demand and Average Demand, respectively. Fig. 11(c) and (d) show the power consumption of the five algorithms for USNET under Random Demand and Average Demand, respectively. It is notable that the results shown in Fig. 11 that the power consumption of the five algorithms all increases with increase of traffic demands. One can easily see from these figures that our proposed VLDMR algorithm performs best in network energy. Since the trend of power consumption curves in all figures is similar, here we take NSFNET as an example for further illustration. As shown in Fig. 11(a), for NSFNET under Random Demand the VLDMR algorithm can save average 38.95% power than the Direct Bypass, 31.05% power than the Multi-hop Bypass, 33.10% power than the PAR, and 29.59% than the MTR. As shown in Fig. 11(b), for NSFNET under Average Demand the VLDMR algorithm can save average 41.78% power than the Direct Bypass, 29.07% power than the Multi-hop Bypass, 31.18% power than the PAR, and 26.94% than the MTR.

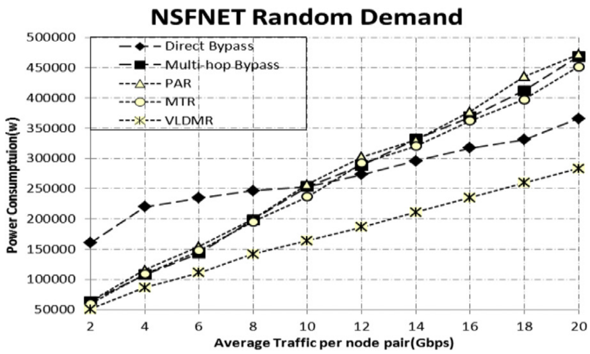
This is because that the first phase of our proposed VLDMR algorithm prefers to construct direct virtual links between connection requests, which means a large amount of traffic only traverse one-hop lightpath to the destination. This method can avoid too much O-E-O conversion and save energy. The second phase of the VLDMR algorithm deletes low-utilization virtual links to further reduce the number of virtual links in the network. The reduction of virtual links can also further reduce network energy. The Direct Bypass is similar with the first phase of VLDMR. When traffic load is low, too much low-utilization virtual links are constructed resulting in energy waste. The Multi-hop Bypass and the PAR prefers to find energy-efficient routing in the current virtual topology and mixed topology (i.e., the combination of the virtual topology and the physical topology), respectively which both induce energy inefficiency (see the example of Fig. 7). The MTR can further reduce network power on the basis of the PAR. But since the PAR use multi-hop grooming strategy, the saving power of the MTR is not notable.

In Fig. 11, for the Direct Bypass, the Multi-hop Bypass and the PAR, we can find that when average traffic per node pair is lower than 10 Gbps, the power consumption curves of the Multi-hop Bypass and the PAR are always below that of the Direct Bypass; when average traffic per node pair is higher than 10 Gbps, the power consumption curves of the Muti-hop Bypass and the PAR are always above that of Direct Bypass. This indicates the Direct Bypass algorithm performs better for high traffic load scenario.

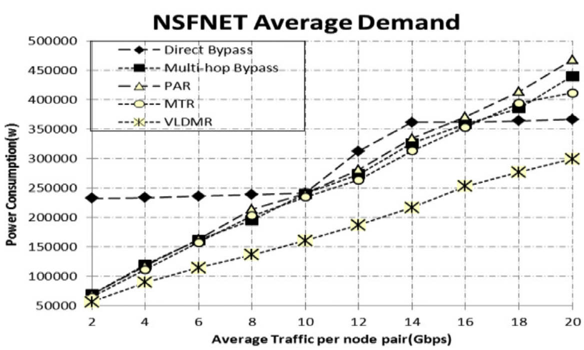
Another interesting observation from Fig. 11 is that gap between the Direct Bypass and our proposed VLDMR. This gap reflects the effect of the second phase of VLDMR which tries to tear down some low-utilization lightpaths of the virtual topology. On the other hand, to compare the power consumption curves of the PAR and the MTR, we can also find the gap between them. But this gap is much smaller than the former. This shows that the virtual topology of the PAR cannot be drastically changed for energy efficiency since all traffic demands are all multi-hop groomed into the virtual links.

5.4. Cross-layer survivability performance

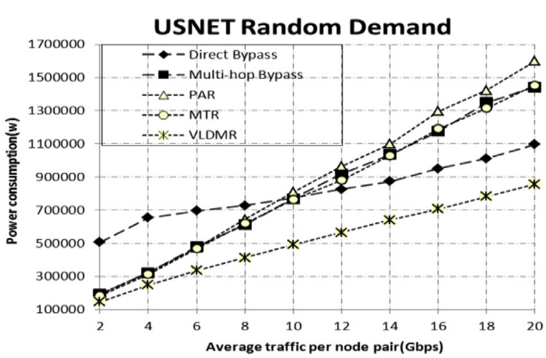
In this part, we investigate the cross-layer survivability performance of our proposed ECSI algorithm. Fig. 12(a) shows the C_w (denoting the maximum number of requests affected by single-link



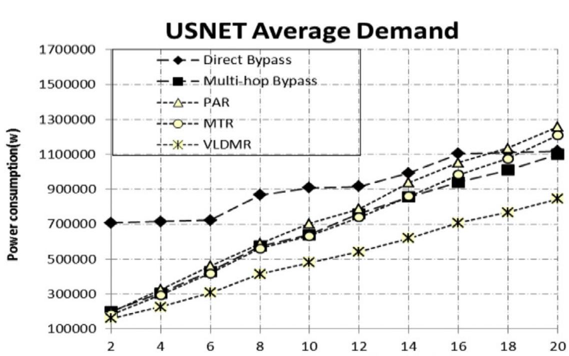
(a) NSFNET in Random Demand



(b) NSFNET in Average Demand

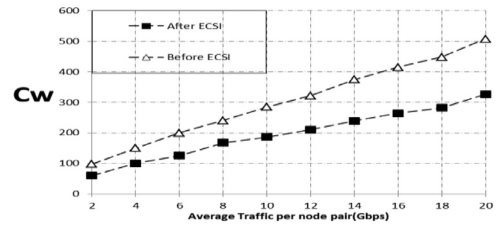


(c) USANET in Random Demand

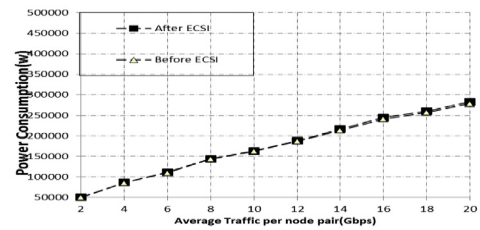


(d) USANET in Average Demand

Fig. 11. Comparion of power consumption of the five energy-efficient algorithms.



(a) Cw value illustration before/after ECSI in the E^2VTD scheme



(b) Power consumption illustration before/after ECSI in the E2VTD scheme

Fig. 12. Illustration for applying the ECSI algorithm in NSFNET.

failure) value and Fig. 12(b) shows the power consumption for applying ECSI algorithm for NSFNET.

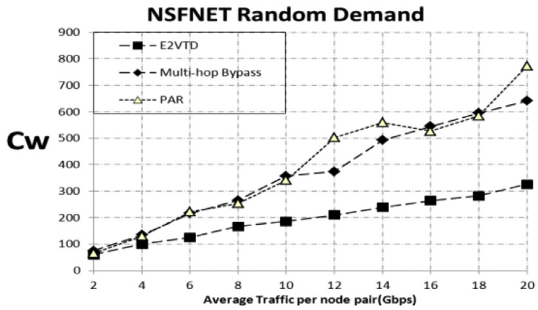
As shown in Fig. 12(a), the value of C_w of two curves increases with the increase of traffic demands. The curve of "after ECSI" is far below that of "before ECSI". This reduction denotes that the ECSI algorithm can enhance the cross-layer survivability significantly. In Fig. 12(a), the reduction of C_w value after the ECSI algorithm ranges from 33 (at average traffic per node pair is 2 Gbps) to 193 (at average traffic per node pair is 20 Gbps), which leads to decrease ranging from about 30.0% to about 38.1%, and in average 34.6%. This means the cross-layer survivability of the network increases 34.6% in average when applying the ECSI algorithm.

As shown in Fig. 12(b), the power consumption curve of "after ECSI" coincides that of "before ECSI" . This denotes the increased power consumption by the ECSI algorithm is negligible. The increase of power consumption for the whole network ranges from about 740 W (at average traffic per node pair is 2 Gbps) to about 4140 W (at average traffic per node pair is 20 Gbps), which leads to increase ranging from about 1.42% to about 1.56%, and in average 1.49%. This result agrees with our explanation about the ECSI algorithm in section IV: The ECSI reroutes some lightpaths in physical topology without building new lightpath. The increased power consumption by the ECSI comes from the added distances and hops of the physical path, which just leads to a slight rise of power consumption.

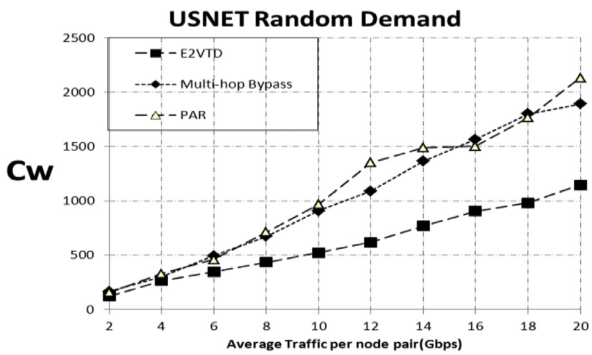
Fig. 13(a) and (b) show the cross-layer survivability C_w of three algorithms under Random Demand for NSFNET and USNET, respectively. We can see that the curve of our proposed E^2VTD scheme (including VLDMR and ECSI) is far below than that of others, which means in the E^2VTD scheme the increase of cross-layer survivability is significant. In particular, for NSFNET, comparing with PAR, the reduction of C_w value ranges from 6 (at average traffic per node pair is 2 Gbps) to 447 (at average traffic per node pair is 20 Gbps), which leads to decrease ranging from about 9.0% to about 58.3%, and in average 43.1%. For USNET, comparing with the Multi-hop Bypass, the reduction in C_w value ranges from 41 (at average traffic per node pair is 2 Gbps) to 821 (at average traffic per node pair is 18 Gbps), which leads to decrease ranging from about 12.3% to about 45.6% and, in average 36.0%.

5.5. Resource performance

In this part, we investigate the network resource of the five energy-efficient algorithms in IP over WDM mesh networks. The



(a) *Cw* value illustration for NSFNET in Random Demand



(b) *Cw* value illustration for USNET in Random Demand

Fig. 13. Cross-layer survivability of three energy-efficient algorithms.

compared algorithms include the Direct Bypass, the Multi-hop Bypass, the PAR, the MTR and our proposed E^{2}VTD (including VLDMR and ECSI).

Fig. 14 shows the network resource performance of the above five algorithms in NSFNET and USNET. Fig. 14(a) and (b) show the number of lightpaths (i.e., virtual links) established by each algorithm. Fig. 14(c) and (d) show the number of wavelength links used by each algorithm. Fig. 14(e) and (f) show the lightpath utilization of each algorithm. Fig. 14(g) and (h) show the bandwidth used of each algorithm. In our paper, the definition of bandwidth used denotes the total used bandwidth in all virtual links, which reflects the really consumed network resource.

As shown in Fig. 14(a) and (b), for the five algorithms the number of lightpaths increases when the traffic loads increases. One can see that the curve of our E^{2}VTD scheme is far below than that of other algorithms. This means that our proposed algorithm consumes the smallest number electronic ports in the network, which is the main cost factor in IP over WDM mesh networks. In particular, for NSFNET of Fig. 14(a), the E^{2}VTD scheme can save average 38.7% lightpaths than the Direct Bypass, 29.3% lightpaths than the Multi-hop Bypass, 31.0% lightpaths than the PAR, and 26.8% than the MTR. We can find that the curves of Fig. 14(a) are similar with the curves in Fig. 11(c) and the curves of Fig. 14(b) are similar with the curves of Fig. 11(e). This agrees with our energy model summarized in section III: Most of the power consumption in two-layer network is used to build new lightpath and more lightpaths means more power consumption.

Fig. 14(c) and (d) show the number of wavelength links used by each algorithm. Note that the number of wavelength links increases when the traffic demands increases. We can see that the curve of our E^{2}VTD scheme is below than that of other algorithms, which means the number of wavelength links used by E^{2}VTD is less than that of others. In particular, for USNET, our E^{2}VTD scheme can save average 36.5% wavelength links than the Direct Bypass, 25.2% wavelength links than the Multi-hop Bypass, 20.2% wavelength links than the PAR, and 14.3% wavelength links than the MTR. This is because the number of wavelength links is mainly determined by the number of lightpaths and the physical path of the lightpath. Although in our E^{2}VTD scheme, the ECSI algorithm adds some hops to the physical path of the lightpath, the number of lightpaths of our E^{2}VTD scheme is far less than that of others. So the E^{2}VTD scheme consumes the least number of wavelength links among all of algorithms.

Fig. 14(e) and (f) show the lightpath utilization of the five algorithms. We can find that, in addition to the Direct Bypass, all of the algorithms have the high lightpath utilization. The reason will be given in the explanation of Fig. 14(g) and (h).

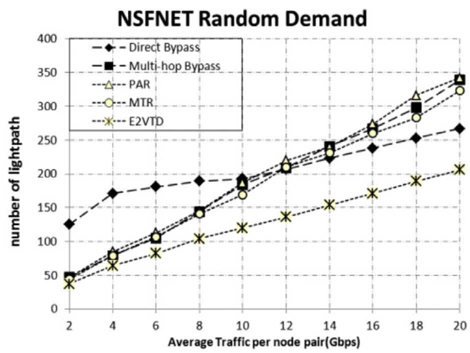
Fig. 14(g) and (h) show the bandwidth consumption of the five algorithms. The curve of "bandwidth requirement" represents the total bandwidth requirement of all the connection requests, which means the theoretical optimum value of the bandwidth consumption. We can see that, in addition to the curve of the Direct Bypass, all of algorithms are above the curve of "bandwidth requirement". As shown in Fig 14(g) and (h), the curves of the Multi-hop Bypass, the PAR, and the MTR are far above than that of "bandwidth requirement", which means the three algorithms waste a large amount of network resource with the non-optimum traffic grooming and routing. For our proposed E^{2}VTD scheme, the curve of E^{2}VTD is just little above that of "bandwidth requirement", which means the network resource efficiency of the E^{2}VTD is the best among all of the algorithms. As to the Direct Bypass, since it constructs the direct lightpath for connection request with one-hop grooming, its consumed bandwidth is identical with that of "bandwidth requirement". However, too many low-utilization lightpaths are constructed in the Direct Bypass, which makes the utilization of the Direct Bypass is far below than that of other algorithms (see in Fig. 14(e) and (f)). We find the Direct Bypass does not achieve network resource efficiency.

5.6. Summary of simulation results

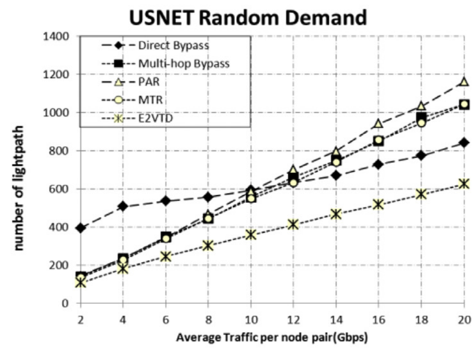
In this section, we compare our E^{2}VTD scheme with the previous algorithms in terms of energy efficiency, resource efficiency and cross-layer survivability. From the above extensive simulation scenarios, we can calculate that our E^{2}VTD scheme outperforms the previous algorithms: network energy consumption is reduced by about 39.8%, network resource is reduced by about 28.2%, and cross-layer topology survivability can be enhanced by about 35.7% in average.

6. Conclusion

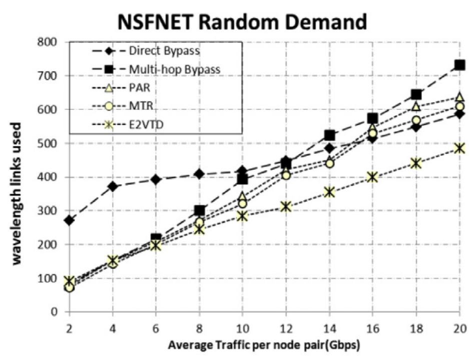
In this paper, we have investigated the problem of energy-efficient topology design for IP over WDM mesh networks. In particular, we propose a novel scheme, namely, E^{2}VTD, for getting a good tradeoff between energy efficiency, resource efficiency and cross-layer survivability efficiency. Our proposed scheme includes two main algorithms. The VLDMR algorithm first initializes the energy-efficient virtual topology by establishing direct virtual links for multi-granularity connections, then reroutes the connections on low-utilization virtual links to further diminish network energy. The ECSI algorithm improves cross-layer survivability of virtual topology by remapping virtual links onto physical links. Simulation results demonstrate the good performance of the E^{2}VTD scheme. Compared with the previous algorithms, network energy consumption is reduced by about 39.8%, network resource is reduced by about 28.2%, and cross-layer topology survivability can be enhanced by about 35.7% in average.



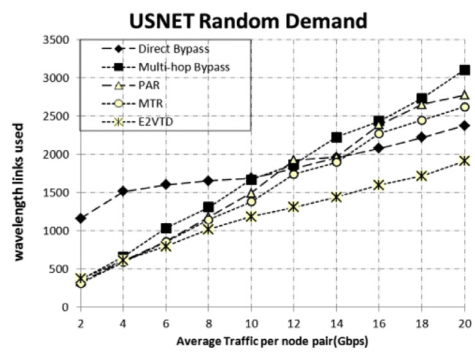
(a) The number of lightpaths in NSFNET



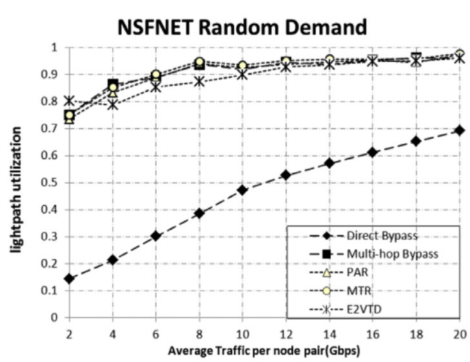
(b) The number of lightpaths in USNET



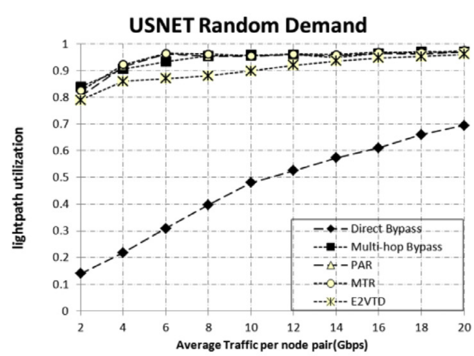
(c) The wavelengthlinks used in NSFNET



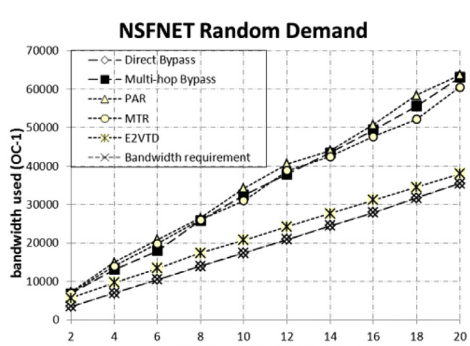
(d) The wavelengthlinks used in USNET



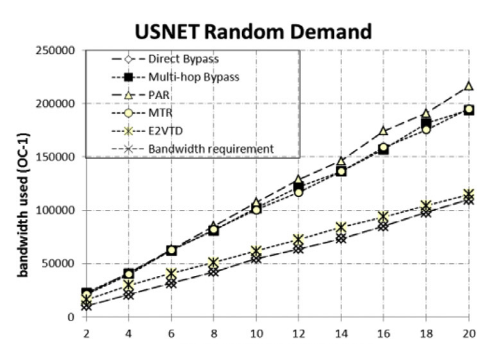
(e) The lightpath utilization in NSFNET



(f) The lightpath utilization in USNET



(g) The bandwidth used in NSFNET



(h) The bandwidth used in USNET

Fig. 14. Comparion of network resource of the five energy-efficient algorithms.

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